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IGNITION AND COMBUSTION CHARACTERISTICS OF METALLIZED PROPELLANTS - PHASE II

Final Report - Phase II
(June 1993-June 1994)
Grant No. NAG 3-1044

Prepared by
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and
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NASA Lewis Research Center

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Bryan Palaszewski
NASA Technical Officer

September 1994

SUMMARY

Experimental and analytical investigations focusing on secondary atomization and ignition characteristics of aluminum/hydrocarbon gel propellants have been conducted. Experimental efforts include the application of a laser-based, two-color, forward-scatter technique to simultaneously measure free-flying droplet diameters and velocities with droplet diameters in the range of 10-200 μm. A diffusion flame burner is used to create a high-temperature environment into which a dilute stream of gel droplets is introduced. Narrowband measurements of radiant emission are used to determine if aluminum ignition in a gel droplet has occurred. A single laser-sheet sizing/velocimetry diagnostic technique, which eliminates sizing bias in the data acquisition process and sizing uncertainties due to a changing particle refractive index, has been designed, constructed and calibrated. Tests involving monodisperse droplet streams of known size are currently in progress.

Models of gel droplet shell formation have been applied to aluminum/liquid hydrocarbon propellants to examine the effects of solid loading and ultimate particle size on the minimum droplet diameter that will permit secondary atomization. For a 60 weight-percent aluminum gel, the limiting critical diameter is predicted to be 34.7 μm, which is somewhat greater than the 20-25 μm limiting diameter determined in the experiments. A previously developed model of aluminum ignition for gel droplets has been applied to the present experiments and predicts ignition times that are in reasonable agreement with experimental results. A model was developed that predicts the mechanical stress in a droplet shell and a parametric study was conducted.

A one-dimensional model of a gel-fueled rocket combustion chamber also has been developed. This model includes the processes of liquid hydrocarbon burnout, secondary atomization, aluminum ignition, and aluminum combustion. Also included is a model for radiant heat transfer from the hot aluminum oxide particles to the chamber walls. Exercising this model shows that only modest secondary atomization is required to reduce propellant burnout distances by more than half, thereby maintaining relatively short chamber lengths. Radiation losses equal to approximately 2-13% of the energy released during combustion were estimated, depending on aluminum mass loading and secondary atomization intensity. A two-dimensional, two-phase nozzle code was employed to estimate nozzle two-phase losses and overall engine performance. Radiation losses resulted in a 1% decrease in engine specific impulse. Results also indicate that secondary atomization may have less effect on two-phase flow losses (4%) than on propellant burnout distance, and may have no effect if oxide particle size is governed by particle coagulation and shear-induced droplet breakup. Engine specific impulse was found to decrease from 337.4 to 293.7 seconds as gel aluminum mass loading was varied from 0 to 70 wt%. Engine specific impulse efficiencies, accounting for radiation and two-phase flow effects, on the order of 0.95 were calculated for a 60 wt% gel, assuming that secondary atomization causes initial droplets to fragment into five equal-sized secondary droplets.

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EXPERIMENTAL EFFORTS

The following list is a brief summary of the experimental efforts over the course of the project. Details can be found in our previous reports and publications listed in Appendix B.

- A single-particle sizing/velocimetry laser diagnostic apparatus for measuring 10-125 μm particles was designed, constructed, and tested.[1-4] In particular, the near-forward scatter, two-color, laser light scattering technique of Wang and Hencken was employed.[5]

- The above system is capable of detecting the presence of burning aluminum in measured particles. Radiant emission from vapor-phase aluminum in the 395-400 nm wavelength region, which only exist during aluminum combustion, is detected using a 395-nm narrow-bandpass filter, a photomultiplier tube, and a low-pass electronic filter.

- A multi-diffusion flame burner,[1-4,6] was designed and constructed. This burner provides a homogeneous post-flame region for studying the combustion and secondary atomization of a dilute, polydisperse stream of 10-125 μm diameter gel droplets. The burner fuel is methane, and the oxidizer is an O_2/N_2 mixture, permitting droplet combustion to be investigated over a range of ambient oxygen concentrations and temperatures. The droplets are generated using a gas-type atomizer mounted in an atomization chamber at the base of the burner.

- A preliminary study of aluminum gel droplet secondary atomization was conducted and the results were compared with theoretical calculations, presented below. These data indicate a smaller minimum droplet diameter for secondary atomization (20-25 μ m) than is predicted by theoretical calculations (34.7 μm). This could be due to experimental uncertainties associated with an unknown and changing particle refractive index or the theoretical assumption of the critical shell thickness required for rigid shell formation.

- Experience with the two-color diagnostic technique revealed limitations in sizing accuracy due to a changing and unknown particle refractive index. Because of these limitations, a single laser sizing/velocimetry technique, based on near-forward Mie scattering, was developed to study 10-125 μm diameter particles in a dilute stream of burning gel droplets.[7,8] Details of this effort are presented in Appendix A.

THEORETICAL/MODELING EFFORTS

Significant findings from the theoretical/modeling portion of our investigation are presented below. Again, more complete information can be found in previous reports and publications, cited in Appendix B.

- Recent studies[9-11] have yielded a simple theoretical framework for aluminum particle shell formation in burning aluminum gel droplets, an event which is considered to be an essential precursor for secondary atomization. This framework has been used to establish criteria for the occurrence of secondary atomization and has been extended to include a specific mechanism for the process leading up to droplet disruption. The following results were obtained:
  - Increasing solids mass fractions and decreasing solid particle diameter are predicted to significantly decrease the minimum diameter gel droplet capable of forming a rigid shell and subsequently undergoing secondary atomization. Calculations indicate that 60 wt% aluminum gel droplets (Al particle size=5 μm) should have a limiting initial diameter of 34.7 μm. Droplets with an initial size smaller than this diameter should be incapable of forming a rigid shell and, consequently, undergoing secondary atomization.
  - Calculations show that gel droplets close to the minimum diameter for rigid shell formation should contain little or no liquid gel after shell sealing. This lack of free gel may reduce the effectiveness of droplet disruption since only shell fragments, rather than secondary droplets, are produced.

- A one-dimensional model of a gel-fueled rocket engine has also been developed to investigate the effects of secondary atomization on propellant burnout distances and radiation losses from the condensed combustion products to the thrust chamber walls.[7,9,10] Calculations for a theoretical upper-stage engine indicate that only moderate secondary atomization, defined as an initial droplet shattering into five secondary droplets, would be required to reduce propellant burnout distance by 62% and radiation losses by 61%. Radiation losses to the chamber walls for a 60 wt% gel are estimated to be approximately 2-13% of the energy released during combustion, depending on aluminum mass loading and secondary atomization intensity.

- The Solid Propellant Rocket Motor Performance Prediction Computer Program (SPP),[11] was employed to estimate nozzle performance losses for the above theoretical engine. Performance calculations, based on an Al_2O_3 particle size distribution determined from the one-dimensional nozzle code, indicate that moderate secondary atomization may only decrease two-phase flow specific impulse losses from 13 to 11.6 seconds. In addition, a literature review of two-phase flow effects in solid motors indicates that secondary atomization may have no effect on two-phase flow losses if the nozzle Al_2O_3 particle size distribution is governed by particle coagulation, agglomeration, and shear-induced breakup.

- Based on the one-dimensional thrust chamber code and SPP calculations, an engine specific impulse efficiency of 0.95 is predicted for a 60 wt% Al gel, assuming that secondary atomization causes each initial droplet to shatter into five equal-size smaller droplets.

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8. Mueller, D. C., and Turns, S. R., " A Laser-Based Sizing/Velocimetry Technique to Investigate the Secondary Atomization of Aluminum Gel Propellants," Penn State Propulsion Engineering Research Center Symposium, NASA-Lewis, Sept. 13-14, 1994.

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APPENDIX A: RECENT EXPERIMENTAL RESULTS

A Laser-Based Sizing/Velocimetry Technique to Investigate the Secondary Atomization of Aluminum Gel Propellants

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SUMMARY:

A laser-based, forward-scatter diagnostic technique, employing a single laser sheet, has been developed to simultaneously measure the size and velocity of individual 10-150 μ m droplets in a dilute polydisperse droplet stream (<1000 particles/cc) and to detect the presence of burning aluminum in these same droplets. Spectral emission from aluminum vapor in the 390-400 nm wavelength region is used as an indication of burning aluminum. The technique utilizes a 4-mm uniformly illuminated probe volume, eliminating trajectory-dependent particle sizing and size-dependent system detection bias. Particle sizing is based on a correlation of particle size with near-forward scattered light intensity. Calculations show average particle sizing variation to be within 3.5% over the expected range of refractive indices. Calibrations using a range of optical pinholes (10-100 μm) were used to verify the above sizing correlation.

DISCUSSION:

Recent theoretical rocket performance studies indicate that aluminum gel propellants, consisting of very fine solid particles suspended in a gelled liquid propellant, may offer increases in engine specific impulse and/or propellant density over conventional liquid propellants.[1-3] Increased propellant combustion times and condensed Al_2O_3 particles in the flowfield, however, may result in sufficient performance losses to eliminate the potential performance gains of aluminum gel propellants.[4] One potential mechanism for reducing these losses is to burn smaller droplets, but the viscous nature of gel propellants may make fine gel atomization difficult to achieve. Fortunately, secondary atomization, in which a droplet spontaneously shatters into a number of smaller droplets due to an internal vaporization of the liquid carrier, may produce the desired small droplets.

Previous research on secondary atomization,[5-7] however, has focused primarily on large droplets (200-1200 μm), while practical applications will require smaller droplets (10-150 μm). Since small-droplet secondary atomization may differ from that of large droplets, primarily due to a difference in the number of aluminum particles present in a given droplet,[8] we are currently investigating the combustion of aluminum/hydrocarbon gel droplets in the range of practical interest (10-150 μm). One objective of the present investigation is to develop non-intrusive diagnostic techniques to study the combustion of 10-150 μm diameter gel droplets. In light of this objective, a laser diagnostic technique, based on near-forward Mie scattering, has been developed to measure the size and velocity of individual droplets in a dilute stream of burning gel droplets and to detect the presence of burning aluminum in these same droplets.

A problem inherent to laser-based sizing systems is the Gaussian distribution of the laser-beam intensity in the radial direction. In a typical system, the probe volume spans the entire beam cross-section, making probe volume illumination non-uniform and scattered light intensity dependent on trajectory through the probe volume. Since particle size is correlated with scattered light intensity, measured particle size in a single-beam system is dependent on trajectory in addition to actual size.[9] In a two-beam laser system, particle trajectory does not play a role in determining measured particle size since a second, coaxially aligned, smaller-diameter beam is used to limit the probe volume to a uniform-intensity region near the center of the sizing beam.[10] In both single and two-beam systems, non-uniform probe volume illumination yields a probe volume cross-sectional area that increases with increasing particle size.[10] Consequently, a system detection bias is introduced, in which smaller particles are underrepresented. While the above phenomena can be corrected for in post-collection processing,[9-11] the material refractive index must be known or constant, and in the case of a single-beam system, all particles must have approximately the same velocity.[9]

Since the shape and refractive index of a gel droplet change as the droplet burns (i.e., Al particle/hydrocarbon $\rightarrow$ Al particle agglomerate $\rightarrow$ molten Al $\rightarrow$ Al_2O_3) and particle velocity may vary significantly because of secondary atomization, the post-collection processing mentioned above can not be employed. Therefore, our system is designed such that the probe volume is uniformly illuminated by a horizontal laser sheet. While this technique eliminates uncertainties associated with a non-uniformly illuminated probe volume, the burning droplet stream and the horizontal slit control the probe volume dimensions, limiting the technique to narrow-diameter droplet streams.

A schematic of the diagnostic system and droplet burner is presented in Fig. 1. In brief, a 1.1-mm diameter He-Ne laser beam (Spectra-Physics 124B) is passed through a 750 mm focal length plano-convex spherical lens (L1, Oriel 40815) and a 19 mm focal length plano-convex cylindrical lens (L2, Newport CKX019), producing a horizontal laser sheet over the burner. This sheet has a calculated $1/e^2$ thickness of 550 μm and a width of 36 mm at the focal point of the lens combination. Gel droplets passing through this sheet scatter light which is collected in the near-forward direction and collimated by a 350 mm plano-convex spherical lens (L3, Oriel 40800), which has a strip of flocking material across its center to block direct laser light. An adjustable aperture (A1, Newport ID-1.5) is used to limit the total light collection angle. The collimated light passing through this aperture is then focused on a 200 μm horizontal slit (S1) by a second 350 mm lens (L4, Oriel 40800). Light passing through this slit is recollimated by a 50 mm plano-convex lens (L5, Oriel 41340) and is separated into two components by a beam splitter cube (BS1, Melles-Griot 03-BSC-009). The first component, used for particle sizing, is refocused through a second 50 mm spherical lens (L6, Oriel 41340), passes through a 632.8 nm line filter (F1, Oriel 52720), two optical diffusers (not shown, Oriel 48010) and enters a photomultiplier tube (PMT) (Hamamatsu R928) where the particle sizing signal is generated. The second component, used to detect aluminum combustion, passes through a 400-nm narrow bandpass filter (F2, Oriel 53800) and enters a second PMT (Hamamatsu R928) to produce the aluminum combustion signal. A detailed discussion of the aluminum combustion system can be found in prior work.[12] A two-channel 20 MHz A/D acquisition board (Rapid Systems 2040) is used to collect the above signals, which are then analyzed using a personal computer.

In general, Mie scattering intensity is highly sensitive to both particle shape and refractive index, making a correlation between scattered light intensity and gel particle size difficult to achieve. Light scattered in the near-forward direction, however, is relatively insensitive to shape and refractive index[13] and can be accurately correlated with particle size over a range of refractive indices. In order to obtain a good sizing correlation, defined as a monotonic function with good insensitivity to refractive index, a parametric study of light collection geometry was conducted. From this study and a consideration of system physical limitations, the scattering response for light collected at a 1.95° angle from the forward direction and over an angle of 1.72° was found to yield the best response. This collection geometry corresponds to a flocking strip thickness of 2 mm and an aperture (A1) diameter of 32 mm.

The series of lines in Fig. 2 shows normalized scattering intensity as a function of particle size for various anticipated material refractive indices calculated using Mie theory.

From this plot it is evident that refractive index variations should affect particle sizing in the 10-125 μm range by at most 12% since the range of refractive indices employed here represents a worst-case scenario. In addition, a range of optical pinholes, which scatter light in the forward direction in the same manner as equivalent particles, were used to verify that the system scattering response matches the theoretical sizing correlation. These measurements demonstrate excellent agreement between the calculated correlation and actual system response. The optical pinholes were also used to verify the uniformity of probe volume illumination.

Figure 3 is a plot of maximum normalized system response as a function of horizontal pinhole location for a number of different size pinholes. From this plot it can be seen that worst-case probe volume response is within 7.5% of maximum in the center 2 mm of the probe volume and 19% for the entire volume. Since virtually all particles will pass through the center 2 mm, the uniformity is quite good. In addition to providing accurate single-particle sizing, the system must be able to perform in a reasonably dense spray without interference from other particles, since signals generated by more than one particle must be rejected. The probability of only one particle being in the probe volume was calculated using a Poission distribution and was found to be reasonable (>50%) for particle number densities of 1000 particles/cc or less.[14]

In summary, the above results indicate that the diagnostic system is performing as expected and should provide accurate particle sizing/velocimetry measurements in a dilute burning droplet stream over a range of material refractive indices. In addition, a uniformly illuminated probe volume is employed to reduce particle size distribution uncertainties associated with a changing material refractive index and/or particle velocity, making this an ideal technique for investigating the secondary atomization of aluminum gel propellants.

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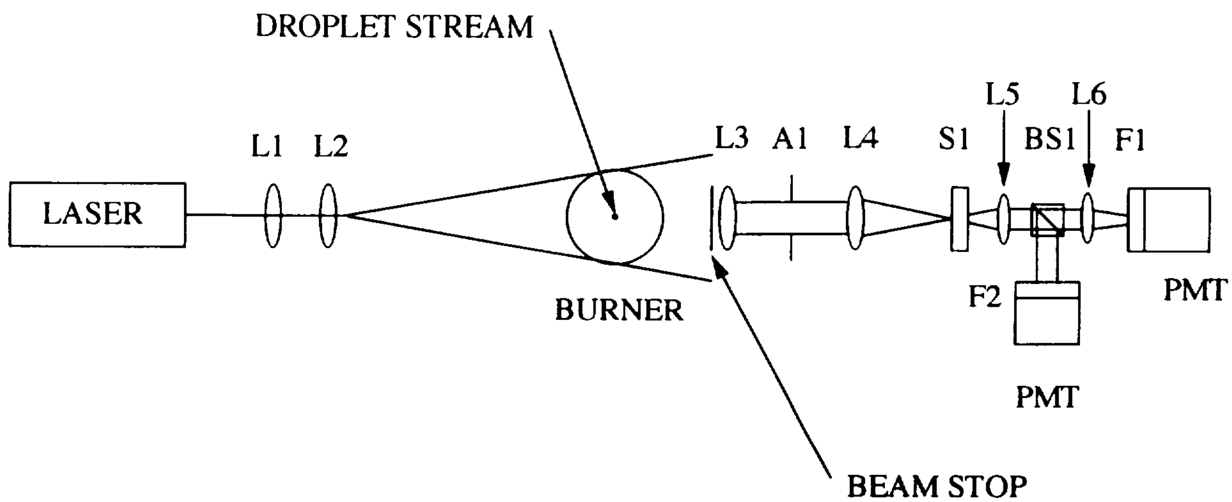

Figure 1. Schematic of the laser diagnostic technique.

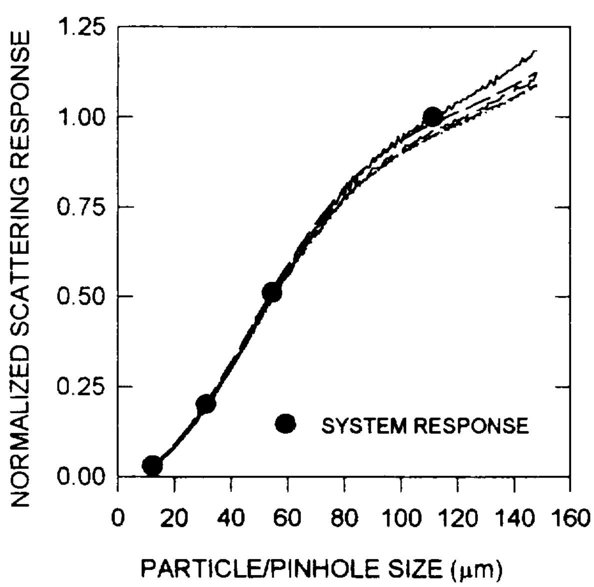

Figure 2. Calculated normalized scattering intensity and actual system response as functions of particle/pinhole diameter.

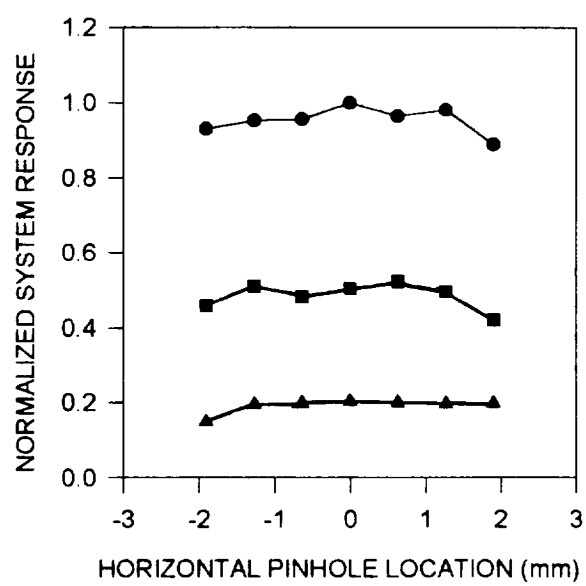

Figure 3. Normalized system response as a function of optical pinhole horizontal position in the probe volume for several pinhole sizes. (● - 111 μm, ■ - 55 μm, ▲ - 31 μm)

APPENDIX B: REPORTS, PUBLICATIONS AND PRESENTATIONS

Reports

1. Turns, S. R., Mueller, D. C. , and Scott, M. J., "Ignition and Combustion Characteristics of Metallized Propellants- Semi-Annual Report," Grant No. NAG 3-1044, January, 1990.

2. Turns, S. R., Mueller, D. C. , and Scott, M. J., "Ignition and Combustion Characteristics of Metallized Propellants- Semi-Annual Report," Grant No. NAG 3-1044, July, 1990.

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7. Mueller, D. C., and Turns, S. R., "Ignition and Combustion Characteristics of Metallized Propellants- Phase II, Annual Report," Grant No. NAG 3-1044, January, 1994.

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1. Turns, S. R., "Ignition and Combustion of Aluminum Slurry Propellants," Penn State Propulsion Engineering Center 1st Annual Symposium at the 25th Joint Propulsion Conference, July 10-13, 1989, Monterey, CA.

2. Turns, S. R., "Ignition and Combustion of Metallized Propellants," Penn State Propulsion Engineering Research Center 2nd Annual Symposium at the NASA Space Transportation Propulsion Technology Symposium, June 25-29, 1990, University Park, PA.

3. Turns, S. R., Mueller, D. C., and Scott, M. J., "Secondary Atomization of Aluminum/RP-1 Liquid Rocket Slurry Fuels," presented at Fall Technical Meeting 1990, Eastern Section: The Combustion Institute, Dec. 3-5, 1990, Orlando, FL.

4. Mueller, D. C., Scott, M. J., and Turns, S. R., "Secondary Atomization of Aluminum/RP-1 Liquid Rocket Slurry Fuels," AIAA Paper No. AIAA-91-3625,

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5. Mueller, D. C., and Turns, S. R., "Aluminized Propellants for Liquid Rockets: Effects of Secondary Atomization on Performance," presented at the Penn State Propulsion Engineering Research Center 4th Annual Symposium, Sept. 9-10, 1992, Marshall Space Flight Center, Huntsville, AL.

6. Mueller, D. C., and Turns, S. R., "Some Aspects of Secondary Atomization of Aluminum/Hydrocarbon Slurry Propellants," *Journal of Propulsion and Power*, Vol. 9, May-June 1993, pp. 345-352.

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9. Mueller, D. C., and Turns, S. R., " A Laser-Based Sizing/Velocimetry Technique to Investigate the Secondary Atomization of Aluminum Gel Propellants," Penn State Propulsion Engineering Research Center Symposium, NASA-Lewis, Sept. 13-14, 1994.